

University of Massachusetts Amherst

ScholarWorks@UMass Amherst

Masters Theses

Dissertations and Theses

March 2019

Legacy Sediment Controls on Post-Glacial Beaches of Massachusetts

Alycia DiTroia

Follow this and additional works at: https://scholarworks.umass.edu/masters_theses_2



Part of the [Geology Commons](#), [Geomorphology Commons](#), and the [Sedimentology Commons](#)

Recommended Citation

DiTroia, Alycia, "Legacy Sediment Controls on Post-Glacial Beaches of Massachusetts" (2019). *Masters Theses*. 738.

https://scholarworks.umass.edu/masters_theses_2/738

This Open Access Thesis is brought to you for free and open access by the Dissertations and Theses at ScholarWorks@UMass Amherst. It has been accepted for inclusion in Masters Theses by an authorized administrator of ScholarWorks@UMass Amherst. For more information, please contact scholarworks@library.umass.edu.

Legacy sediment controls on post-glacial beaches of Massachusetts

A Thesis Presented

By

ALYCIA L. DITROIA

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

February 2019

Department of Geosciences

Legacy sediment controls on post-glacial beaches of Massachusetts

A Thesis Presented

By

ALYCIA L. DITROIA

Approved as to style and content by:

Jonathan D. Woodruff, Chair

Stephen B. Mabee, Member

William P. Clement, Member

Julie Brigham-Grette, Department Head
Department of Geosciences

ABSTRACT

LEGACY SEDIMENT CONTROLS ON POST-GLACIAL BEACHES OF MASSACHUSETTS

FEBRUARY 2019

ALYCIA DITROIA, B.S., UNIVERSITY OF MASSACHUSETTS AMHERST

M.S., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Jonathan D. Woodruff

Here we examine seasonal grain-size trends on 18 beaches in the Northeastern US and dispersed along the post-glacial coast of Massachusetts (USA) in order to explore the mechanisms influencing median grain size and slope. Over 800 grain size samples were collected along 200 summer and winter cross-shore beach elevation surveys. Obtained grain size and beach slope data are compared to coastal morphology, sediment source, wave height, and tidal magnitude in order to ascertain controls on beach characteristics. In general, median grain size increases with intertidal beach slope in the study region. However, grain sizes along post-glaciated beaches in the study are as much as an order of magnitude coarser for the same beach slopes when compared to beaches for other regions of the US. Grain size and slope for beaches in the northeastern US also exhibit less correlation with oceanographic processes (i.e. wave climate and tidal magnitude). Instead, grain size trends are primarily driven by the composition of nearby glacial deposits that serve as the primary source of sediment to beaches in the study region. Results provide quantitative support for the distribution and composition of legacy glacial deposits rather than oceanographic conditions serving as the predominant governor of beach grain size along post-glaciated coastlines of the Atlantic continental margin.

TABLE OF CONTENTS

	Page
ABSTRACT	iv
LIST OF FIGURES.....	vi
CHAPTER	
1. INTRODUCTION.....	1
2. METHODS.....	4
3. BACKGROUND ANALYSES.....	6
3.1. Oceanographic Characterization.....	6
3.2. Geomorphic Setting.....	6
3.3. Surficial Sediments.....	7
3.3.1. <i>North Shore</i>	7
3.3.2. <i>South Shore</i>	9
3.3.3. <i>Cape Cod and the Islands</i>	9
3.3.4. <i>Southeast of Cape Cod</i>	10
4. RESULTS.....	11
4.1. Grain Size vs. Beach Slope.....	11
4.2. Wave Breaking Criterion.....	11
4.3. Geomorphic Classification vs. Grain Size.....	12
4.4. Source Material vs. Grain Size.....	12
4.5. Shoreline Change.....	13
5. DISCUSSION AND CONCLUSIONS.....	14
6. BIBLIOGRAPHY.....	27

LIST OF FIGURES

Figure	Page
1. Study Sites.....	15
2. Salisbury Beach Transect E Example.....	16
3. Example of Seasonal Transect Data.....	17
4. Mean off-shore Wave Height vs. Tidal Range.....	18
5. Geomorphic Classification of Massachusetts.....	19
6. Surficial Geology of Massachusetts.....	20
7. Beach Averaged Inter-tidal Beach Slope vs. Inter-tidal Median Grain Size.....	21
8. Beach Averaged Beach Slope vs. Median Grain Size for MA & US. Beaches.....	22
9. Irribaren Number (ξ) vs. Surf Scaling Parameter (Ω).....	23
10. Beach Averaged Median Grain Size vs. Geomorphology.....	24
11. Beach Averaged Median Grain Size vs. Source Material.....	25
12. Shoreline Change vs. Beach Averaged Median Grain Size.....	27

CHAPTER 1

INTRODUCTION

Sand and cobble beaches are dynamic systems that compose 16 percent of our world's coastline, (Martinez, 2006) and often serve as the primary line of flood defense for populations residing on and behind them. Grain size is a defining feature of these beach systems, central in driving their morphology (Fitzgerald & Van Heteran, 1999), as well as their erosional and depositional response to storms and changing sea level (Zhang, 2001; Bruun & Gerritsen, 1961).

Methods for characterizing beaches extend back several decades with most early works linking their sedimentology to beach morphology and near-shore oceanographic conditions including waves and tides. A positive correlation between median grain size (D_{50}) and inter-tidal beach slope has been observed for beaches along part of the western coast of the United States (Bascom, 1951; Weigel, 1964). Wave climate and grain size were further observed as the predominant governors of beach slope (Wiegel, 1964) using additional data collected along the eastern coast from New Jersey to Florida (The Beach Erosion Board, 1933). These observations were consistent with earlier observations (The Beach Erosion Board, 1933) for beaches in New Jersey, showing that coarser, steeper beaches tended to erode less during high wave activity (Dean and Dalrymple, 2001).

To better constrain wave breaking conditions on a beach and resulting grain size characteristics, the surf-scaling parameter (Guza & Inman, 1975), is one parameter used to divide beaches into three primary categories: reflective, dissipative, and intermediate. Here, dissipative beaches typically are categorized by their gentle slope with short energetic waves that are absorbed in the nearshore zone. These beaches tend to have large intertidal zones composed of fine sediment (Short & Wright, 1983). Reflective beaches are the opposite, with steeper slopes and low energy waves, creating an almost non-existent intertidal zone composed of coarse sediment (Short & Wright, 1983). Intermediate beaches have characteristics that are in between reflective and dissipative.

Assuming a correlation between grain size and beach slope, the surf scaling parameter was expanded on (Guza & Inman, 1975) to define breaking conditions on a beach based on its predominant grain size (i.e. D_{50}) utilizing the Australian coastline, (Short and Wright, 1984). In this grain size approach, a non-dimensionless fall velocity (Ω) has been proposed for delineating breaking wave conditions (Gourlay & Van der Meulen, 1968) based on breaking wave height (H_b), wave period (T), and grain size (w_s):

$$\Omega = \frac{H_b}{w_s T}$$

Assuming a direct relationship between grain size and beach slope, values of Ω are found to be generally > 5.5 for dissipative conditions, < 1.5 for reflective beaches, and in between for intermediate conditions (Wright et al., 1984; Masselink & Short, 1993; Masselink et al, 2011).

Another widely used and more direct formula in beach categorization is the Iribarren number (ξ , Battjes, 1974):

$$\xi = \frac{\beta}{(H/L_o)^{1/2}}$$

Here, β is beach slope, L_o is deep-water wavelength, and H is the significant wave height for either breaking (H_b) or deep water (H_o) waves. In comparison with Ω (that assumes a link between grain size and beach slope), the Iribarren number directly compares wave steepness and beach slope to infer breaking wave conditions.

In addition to local wave and tidal conditions, antecedent post-glacial geology has been highlighted in the Northeastern US as a primary control on beach morphology and grain size (Fitzgerald & Van Heteran, 1999). When classifying beaches in the region several barrier-coastline types controlled primarily by sediment availability have been identified, (Fitzgerald & Van Heteran, 1999). These include: sediment starved and isolated systems ‘Type 1’; headland separated with small local

updrift and off-shore sediment sources ‘Type 2’; beaches with larger updrift and glaciofluvial deposits that include mainland-segmented ‘Type 3’; and inlet-segmented ‘Type 4’. ‘Type 3’ and ‘Type 4’ beaches are subdivided further into wave-dominated (‘Types 3a’ and ‘4a’) and mixed-wave-tidal-energy (‘Type 3b and 4b’) zones (Fitzgerald & Van Heteran, 1999). These results and categorizations (Fitzgerald & Van Heteran, 1999) highlight the importance of underlying geology and stress the importance of sediment source in categorizing beach morphologies and basic sedimentary characteristics, particularly for post-glacial coastlines of the northeastern US.

Observations by Fitzgerald & Van Heteran (1999) provide an important qualitative link between sediment source and beach sedimentology. However, regional acquisition and synthesis of quantitative grain size data for the northeastern US has yet to be presented. In this paper, we expand on the work of Fitzgerald & Van Heteran (1999) by presenting an extensive data set of seasonal grain sizes and inter-tidal beach slopes for post-glacial beaches of the northeastern US. Further, we investigate these dynamic beaches, generally eroding and unengineered, across a range of grain sizes and materials to determine how sediment source affects/fits into classical beach characterization schemes. Results provide quantitative support for the dominance of legacy sediments over oceanographic conditions as a primary control on grain size in the region. Observations are focused to the beaches of Massachusetts, but with trends and findings that are applicable to post-glaciated coastlines throughout the Atlantic continental margin.

CHAPTER 2

METHODS

The study area extends from the northern most coast of Massachusetts at Salisbury Beach, south to the Massachusetts-Rhode Island border at Westport Beach. It also includes beaches on the islands of Nantucket, Martha's Vineyard and Cuttyhunk (Figure 1). Sites were selected in collaboration with the Massachusetts Office of Coastal Zone Management (MA CZM) and U.S. Bureau of Ocean Energy Management (BOEM) in order to identify public beaches in need of sediment characterization throughout the state.

An updated characterization of oceanographic and geological conditions for study sites was initially conducted following methods similar to Fitzgerald and Van Heteran (1999). Tidal range at each site was obtained based on an interpolation between available NOAA tidal gauge stations (<https://tidesandcurrents.noaa.gov>), while off-shore wave conditions for each beach are based on wave climatology derived from 3.5 years of simulations between 2014 and 2018 by the United States Geological Survey (USGS) Coupled Ocean-Atmospheric-Wave-Sediment Transport (COAWST) model (Warner et al., 2010). Shoreline change was computed from the Massachusetts Office of Coastal Zone Management using the Shoreline Change Browser in the Massachusetts Ocean Resource Information System (MORIS). The shoreline change rate data is comprised of both aerial photographs, as well as over 2000 LIDAR images within 50-meter intervals used to help resolve uncertainties over a 30-year period (i.e. short-term analysis) (Thieler et al., 2013). Shoreline change rates were overlain over each beach transect in this study using ArcGIS (Version 10.4.1). Detailed descriptions of sediment sources for each beach are based on analysis of updated USGS maps of surficial geology (Stone et al., 2006; Stone et al., 2011; Stone and DiGiacomo-Cohen, 2009; Stone et al., 2018).

Sediments at each beach were primarily characterized for the inter-tidal zone from low to high tide as this region has been found to be the most effective predictor of long-term beach behavior

(Stauble, D.K, 2005). Approximately 4-9 intertidal transects were conducted for each of the 18 beaches. Transect positions were chosen along representative locations on the beach and equally spaced when possible. Sampling was designed to assess grain size distributions near mean high water, mid-tide and near mean-low water. To assess temporal variations in grain size these beach foreshore sites were sampled both during the end of the summer and winter seasons. At locations primarily composed of sand and gravel (i.e. $< 64\text{mm}$), surface samples of the top $\sim 15\text{ cm}$ were collected and brought back to the University of Massachusetts for analysis. Grain sizes for sampling locations composed primarily of pebble and cobbles ($>64\text{ mm}$), were measured in the field using a gravelometer and standard pebble count techniques (Wolman, 1954). Inter-tidal beach slope for each transect was obtained based on the elevation profiles obtained either using a Real Time Kinematic (RTK) GPS tied into a local reference station or standard survey equipment tied to local benchmarks.

Once back in the lab all sediment samples were washed and dried thoroughly to remove salt and debris (sticks, bark, etc.). Each sample was weighed and sub-divided to fractions greater and less than 4 mm . Distributions for grains greater than 4 mm were obtained via standard sieving techniques (Udden, 1914; Wentworth, 1922). Grain size distributions for sample fractions $<4\text{mm}$ were measured on a CAMSIZER particle image grain size analyzer capable of measuring grain sizes for particles between $30\text{ }\mu\text{m}$ and 4 mm . Complete grain size distributions were obtained by combining sieve and CAMSIZER sample results weighted by the measured fraction of total sample run on each. See Figure 2(a-b) and 3(a-c) for examples of grain size and survey data collected at a representative beach (Salisbury).

CHAPTER 3

BACKGROUND ANALYSES

3.1. Oceanographic Characterization

Figure 4 presents the wave/tide oceanographic categorization of beaches in this study according to the classification proposed by Hayes, (1979). Tidal ranges in Massachusetts Bay vary between 2-3m and are much larger than that observed south of Cape Cod, where the range is generally less than 1 m (Irish and Signell, 1992). In contrast, wave heights are generally smaller in Massachusetts Bay due to more sheltered conditions relative to the open Atlantic side of Cape Cod and the Islands. Large tides and smaller waves, results in predominantly tide-dominated conditions for most beaches in Massachusetts Bay (Figure 4). The exception to this is Long Beach in Rockport, MA (referred to as Rockport in this study) due to its location near the southern tip of Cape Ann where wave heights are significantly greater. In contrast, due to a relatively small tidal range, all study beaches on the south side of Cape Cod and the Islands experience wave-dominated conditions.

3.2. Geomorphic Setting

The geographic distribution of the six geomorphic beach types proposed by Fitzgerald and Van Heteran (1999) in Massachusetts are presented in Figure 5. Ordered from predominantly large to small grain size these types include ‘Type 1’- isolated, ‘Type 2’- headland separated, ‘Type 3’- mainland segmented and ‘Type 4’- inlet-separated. ‘Type 1’ beaches are high relief and compartmentalized along the coastline, with surficial material composed primarily of bedrock and small isolated sediment sources. No beaches within the study fit ‘Type 1’ criteria. ‘Type 2’ headland separated beaches are composed of short narrow barriers with multiple sediment sources that can be mobilized either by mixed-energy or wave-dominated conditions. A majority of beaches in the study are classified as ‘Type 2’. These include the mixed tide/wave energy beach at Rockport (or Long Beach), the tide-dominated beaches of Nahant, Revere, Nantasket, Peggotty, Humarock

and Marshfield, and the wave-dominated beaches of Barges, East and Horseneck. ‘Type 3’ are mainland segmented beaches with moderately long sand-dominated barriers and are explicitly divided into wave-dominated (3a) and mixed energy (3b). Surf, Town, Sylvia, Low, and Miacomet represent ‘Type 3a’ beaches in the study, while Plymouth represents the sole ‘Type 3b’ beach. Finally, ‘Type 4’ inlet segmented beaches are generally composed of long single barrier beach systems with few segments and a significant sediment source (Fitzgerald & Van Heteran, 1999). Plum Island and Salisbury represent the two ‘Type 4’ beaches in the study and are further classified as mixed-energy (i.e. Type 4a).

3.3 Surficial Sediments

Much of the surficial sediments in New England, including Massachusetts, were formed and initially deposited during past glaciations in the late Pleistocene (Figure 6). In turn the morphologies proposed by Fitzgerald & Van Heteran, (1999) are heavily influenced by local glacial history, which also largely defines the sources of sediment to individual beach systems. A discussion on the primary coastal regions of Massachusetts and their respective local sediment sources are provided below. These regions include the North Shore (from the New Hampshire boarder south to Boston), South Shore (Boston south to Cape Cod), Cape Cod and the Islands, and the east coast of Buzzards Bay west to the Rhode Island boarder.

3.3.1. North Shore

Glacial legacy sediments are sparsely distributed over the landscape in New England, resulting in a regional coastline that is generally sediment starved relative to other regions of the US (Fitzgerald & Van Heteran, 1999). However, along the northern most coastal region of Massachusetts, where Salisbury and Plum Island beaches are located, rapid marine inundation occurred following ice retreat, which deposited a layer of fine-grained marine sediments over till. Isostatic rebound produced a rapid relative sea level drop allowing the post-glacial Merrimack River to deposit a

veneer of fluvial sediments and an offshore delta (Hein et al., 2014). Foreset beds are evident in offshore seismic records (Barnhardt et al., 2009). Holocene marine transgression reworked the delta and fluvial deposits providing the primary source for sediments that comprise the ‘Type 4a’ beaches of Salisbury and Plum Island. The coarse stratified deposits from which these beaches were derived are well-sorted to poorly-sorted gravel, sand, silt and clay and can be categorized into three distinct textural units; gravel deposits, sand and gravel deposits, and fine deposits (i.e. <256 mm) (Stone et al., 2006).

Long Beach, in Rockport, along the south side of Cape Ann (referred to as Rockport in this study), is a pocket ‘Type 2’ beach comprised of fine sand enclosed by two bedrock headlands at each end. A small back-barrier creek also supplies fine grained sediment to Rockport beach.

Nahant and Revere are two ‘Type 2’ headland separated beaches located immediately north of Boston. Nahant Beach, a tombolo connecting the town of Nahant with the city of Lynn, is sourced on the east side by the erosion and longshore transport of reworked drumlin till. On the west side, erosion of coarse stratified deposits may have contributed sediment. Revere Beach is located near an isolated outwash plain of coarse stratified sediments and is the likely original source of material for the beach. Coarse deposits, specifically within these glacially stratified units, range from 25 to 50 percent gravel, 50 to 75 percent sand particles and vary from well to poorly sorted. The sand deposits within this unit are composed mainly of very coarse to fine sand with coarser layers containing up to 25 percent gravel. However, both Nahant and Revere have received allochthonous fine-grained material during beach nourishment projects in the years prior to this study. This includes a major dune restoration project on Nahant Beach in 2014 (Patrick, 2014), and a large replenishment project on Revere Beach in 1991 (<http://www.nae.usace.army.mil/Missions/Civil-Works/Shore-Bank-Protection/Massachusetts/Revere/>). Annually, Revere Beach also receives up to 10 tons of sand for a July sand castle building contest (Revere Beach Partnership (501(c)(3) Non-Profit Organization).

3.3.2. South Shore

Nantasket Beach, located immediately south of Boston, is the first of four ‘Type 2’ headland-separated beaches in this study located along the South Shore of Massachusetts. Nantasket Beach is juxtaposed to several drumlins, including several eroded offshore, that likely serve as the main source of sediment to the beach. Peggotty, Humarock and Marshfield beaches receive most of their sediment from the erosion of glacial till. However, coarse stratified deposits provide a secondary source of sediment to Peggotty and Marshfield. Plymouth Beach is located to the south of Marshfield and is a ‘Type 3a’ mixed-wave-tidal-energy mainland segmented beach that lies adjacent to an extensive, coarse grained ice contact deposit characterized by very hummocky, pocked marked kame and kettle terrain.

3.3.3. Cape Code and the Islands

Surf Beach, located on the south side of Cape Cod, is a ‘Type 3b’ mainland segmented, wave dominated beach. The beach is situated at the contact between the Buzzards Bay recessional moraine and the corresponding, distal outwash plain, receiving contributions from both sources. The moraine contains many boulders in a very sandy matrix. Barges Beach ‘Type 2’, on Cuttyhunk, lies directly on the Buzzards Bay recessional moraine which contains mostly gravel and cobbles.

The Islands of Martha’s Vineyard and Nantucket contain two main surficial deposits, till associated with the Late Wisconsinan terminal moraine and glacial outwash deposited by meltwater emanating from the terminal moraine. The terminal moraine deposits are comprised mostly of boulders and sandy upper till (Stone and DiGiacomo-Cohen, 2009). Sylvia State Beach on Martha’s Vineyard is a ‘Type 3b’ beach sourced from both the sandier component of the till and coarse stratified outwash deposits, whereas Town Beach (also ‘Type 3b’) is sourced primarily from till that contains a higher gravel/cobble component. In contrast, Miacomet and Low Beaches on Nantucket are sourced completely by the medium-to-coarse sand from glacial outwash.

3.3.4. Southeast of Cape Cod

The last two study sites are ‘Type 2’ beaches, Horseneck and East, located on the western most portion of mainland Massachusetts bordering the state of Rhode Island. These two beaches are formed by the direct erosion of glacial till (not drumlins), with very little winnowing by longshore transport.

CHAPTER 4

RESULTS

4.1 Grain size vs. Beach Slope

In general, median (D_{50}) grain size increases with average inter-tidal slope for Massachusetts beaches (Figure 7). Seasonally, beaches also tended to coarsen between summer and winter surveys. However, seasonal changes in beach slope were far less significant, and in most cases no significant change was observed between summer and winter surveys. The two greatest exceptions to this seasonal stability are East Beach and Miacomet whose slopes increase (summer to winter) from 0.09 to 0.16 and 0.07 to 0.11, respectively. In general, beaches along the Massachusetts coast are also significantly coarser for the same beach slope when compared to other regions of the US (Figure 8). Grain sizes for Massachusetts beaches also show less correlation with beach slope, exhibiting roughly a two order of magnitude range in grain size (0.3mm to nearly 30mm) for a beach slope range of only 0.08 to .15 (Figure 7).

4.2. Wave Breaking Criterion

Figure 9 provides a comparison of the Iribarren number classification of wave breaking conditions to those proposed with the dimensionless fall velocity (Ω). A majority of the beaches are intermediate as classified by the more direct Iribarren number (13 of the 18), with the remaining finer grained beaches exhibiting dissipative conditions. The less direct omega metric for breaking conditions based on grain size to infer beach slope was somewhat effective in classifying dissipative conditions (3 of the 5). However, six of the twelve intermediate beaches (as defined by the Iribarren Number) were falsely classified as reflective in accordance to the omega metric. These beaches represent some of the coarsest in the study (Humarock, Marshfield, Town, Surf, Barges, and Horseneck), but with anomalously shallow beach slopes similar to finer grained beaches correctly classified as intermediate (Salisbury, Plum Island, Peggotty, Low, Miacomet, Sylvia).

4.3 Geomorphic Classification vs. Grain Size

Fitzgerald & Van Heteran (1999) geomorphic beach types are compared to median grain size for each beach in Figure 10. In general the median grain size for beaches (D_{50}) decreases with increasing beach type (1-4), a finding consistent with that proposed by Fitzgerald & Van Heteran (1999). However, the grain size range for beaches of an individual beach type varies widely. This is particularly apparent for the most prevalent headland separated ('Type 2') beaches in the study, where grain sizes extend over two orders of magnitude, and contain two of the finest nourished beaches in the study (Revere and Nahant) as well as two of the coarsest (Horseneck and Barges). The mainland segmented ('Type 3b') beach of Plymouth was also observed to be finer (D_{50} = 0.3 mm) than the 'Type 4' inlet segmented beaches of Plum Island and Salisbury (D_{50} = 0.8 mm and 0.7 mm, respectively). D_{50} grain sizes for the 'Type 3a' Nantucket beaches of Low and Miacomet were also similar to Plum Island and Salisbury.

4.4. Source Material vs. Grain Size

Maps of surficial sediment distributions shown in Figure 6 were employed to identify the primary sedimentary units that serve as sources of sediment to each beach in the study (Figure 11). In order of increasing grain-size and decreased sorting these predominant sources include: 1. coarse stratified deposits, 2. a mixing zone of coarse stratified deposits and till, and 3. drumlin till and/or glacial till (ground moraine). Average grain size for beaches in the study generally relate to grain sizes observed within the predominant source material selected for each beach. The nourished beaches of Nahant and Revere are some of the finest grains, followed by beaches supplied predominantly by coarse stratified drift (Plum Island/Salisbury complex, Plymouth, and the Nantucket Beaches of Low and Miacomet). Beaches sourced by a mixture of coarse stratified drift and till (Sylvia, Surf, Town, Marshfield and Peggotty), generally exhibit an increase in grain size

with percent till sourcing. For example, Sylvia, Surf, Town, Marshfield and Peggotty generally increase in both percent till sourcing and grain size. Beaches southwest of Cape Cod sourced predominantly by till are the coarsest in the study and include Barges, Horseneck and East. Nantasket is an exception to the predominant trend of increasing grain size with increasing percentage of till for a source material, which is located near major drumlins both on and off-shore (sourced by drumlin till). The predominant source of sediment to Rockport is unclear. It is predominantly surrounded by bedrock, however, a small creek behind the barrier beach flows through a local coarse stratified drift deposit which likely results in the finer grain sizes observed at the site.

4.5. Shoreline Change

Rates of shoreline change along individual beach transects varies widely (Figure 12). For example, over half of the beaches in the study (10 out of 18) had some transects that were erosional and some accretional. Average rates of shoreline change at a certain beach (either erosional or accretional) for all transects were generally less than ± 0.5 m/yr (14 out of 18 beaches). Exceptions to this include the accreting beach of Plymouth that was just above 1 m/yr, and the predominantly eroding beaches of Salisbury, Plum Island and Peggotty all having average rates of erosion of between 1.2 and 1.4 m/yr. In general, predominantly accreting beaches were finer grained (e.g. of the 7 predominantly accretional beaches 6 had an average grain size less than 1.5 mm). Fine grained exceptions to this include the predominantly eroding beaches of Nahant, Plum Island and Salisbury. Conversely, predominantly eroding beaches were generally coarser grained (e.g. 8 of 11 predominantly eroding beaches had average grain sizes greater than 1.5 mm). The single coarse-grained exception to this was Barges whose average accretion rate was ~ 0.5 m/yr.

CHAPTER 5

DISCUSSION AND CONCLUSION

In general, a direct relationship is observed between grain size and beach slope for Massachusetts beaches in the study (Figure 7). However, this relationship is relatively weak when compared with West Coast and more southern East Coast beaches (Figure 8). With less correlation between grain size and beach slope the grain size dependent metric Ω serves as a poor predictor of wave-breaking conditions (Figure 9). Further, unlike some other areas of the US (Wiegel, 1964), oceanographic factors (i.e. tides and waves) are not the predominant control on grain size for our study sites (Figure 4 and Figure 1). For example, the wave dominated beaches of Horseneck, East and Barges, and the tide-dominated beaches of Marshfield and Humarock are among the coarsest beaches in the study, while the wave dominated beaches of Sylvia and Low and the tide-dominated beaches of Salisbury, and Plum Island are among the finest. Similarly, absolute wave height and tidal elevation exhibit also a poor correlation with beach grain size.

The geomorphic categories of Fitzgerald and Van Heteran (1999) show a reasonable correlation with grain size (Figure 10). However, grain sizes can vary by an order of magnitude for beaches of a particular geomorphic type. Stronger correlations are observed between grain size and the primary sediment source. This source to sink comparison likely provides a more direct relationship, with geomorphic type indirectly linked to the predominant sediment type for a particular location. Rates of shoreline change can vary widely between transects at a particular beach. Even so, some correlation was observed between grain size and shoreline change, with finer grained beaches generally exhibiting accretionary conditions and coarser beaches erosional. This is likely a result of greater sediment availability and in turn stability for finer grained beaches. Results provide further understanding of typical drivers of grain size on beaches, and the importance of local sediment sources in governing beach characteristics, particularly for post-glacial systems like the Northeast that are in general sediment-starved.

Figure 1: Study Sites: Site map with location of field sites (red circles) and field photos of 8 of the 18 beaches.

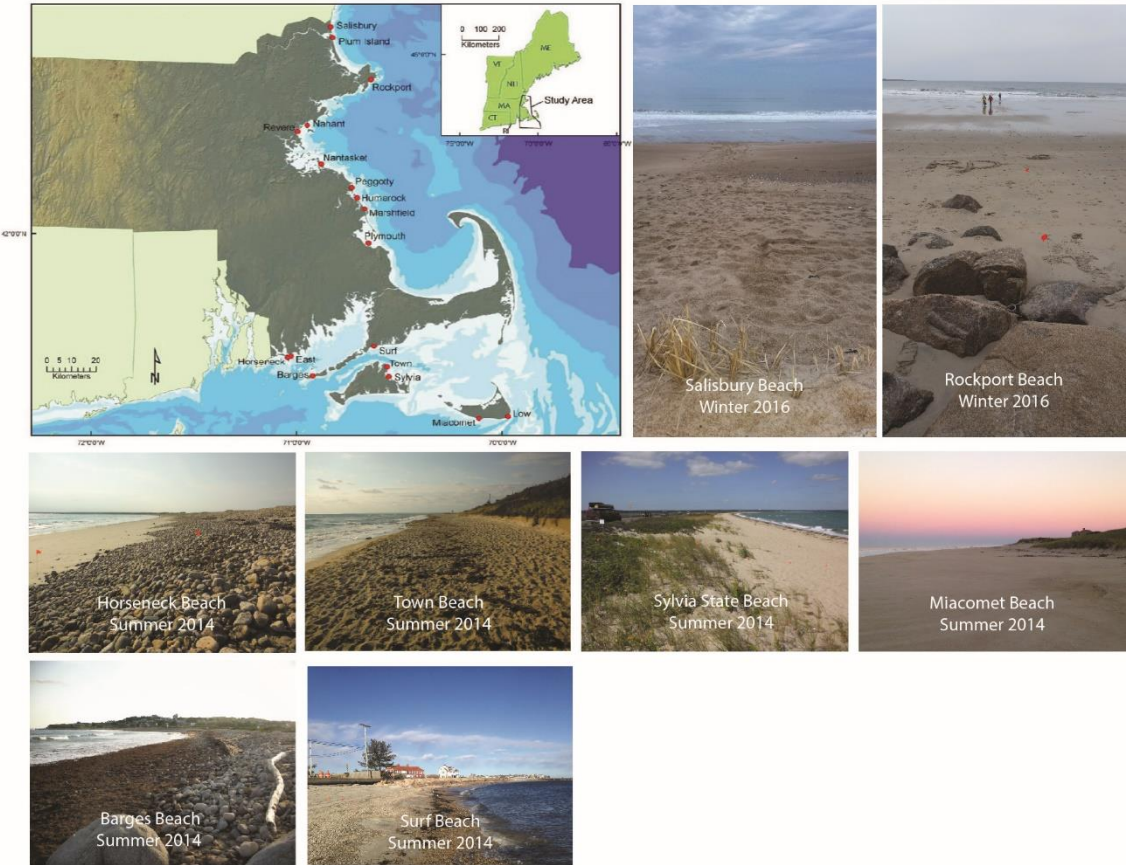


Figure 2: Salisbury Beach Transect E Example: (A) Example of transects from Salisbury Beach along with past shore-line locations obtained from MA CZM. (B) Example of data collected at Transect E on Salisbury Beach. Upper left panel in B provides location of Transect E, while upper right plots the winter (blue) and summer (red) beach profiles for the transect. Lower three panels in B correspond to the cumulative grain size distribution measured in the winter (blue) and summer (red) at the location of high-tide (lower left), mid-tide (center) and low-tide (lower right).

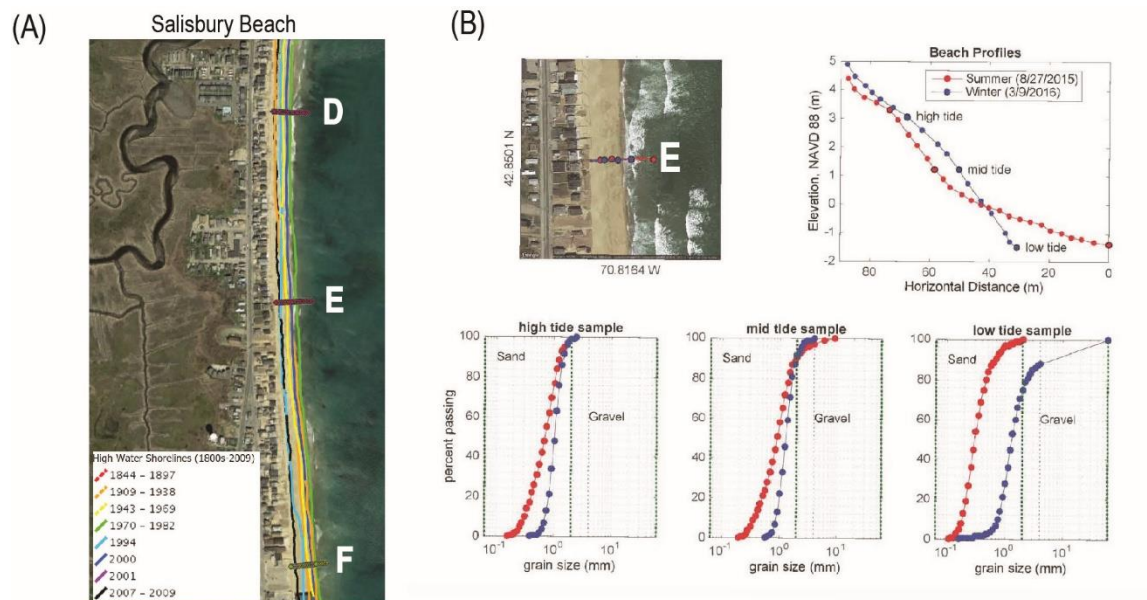


Figure 3: Example of Seasonal Transect Data: Example of seasonal transect averages of median grain size (summer – red; winter – blue) (A) and inter-tidal beach slope (summer – purple; winter – turquoise) (B) for Salisbury Beach. Average annual shore-line change observed at each transect is shown in (C) and based on MA CZM analysis of aerial photos over the last ~30 years (<https://www.mass.gov/service-details/massachusetts-shoreline-change-project>).

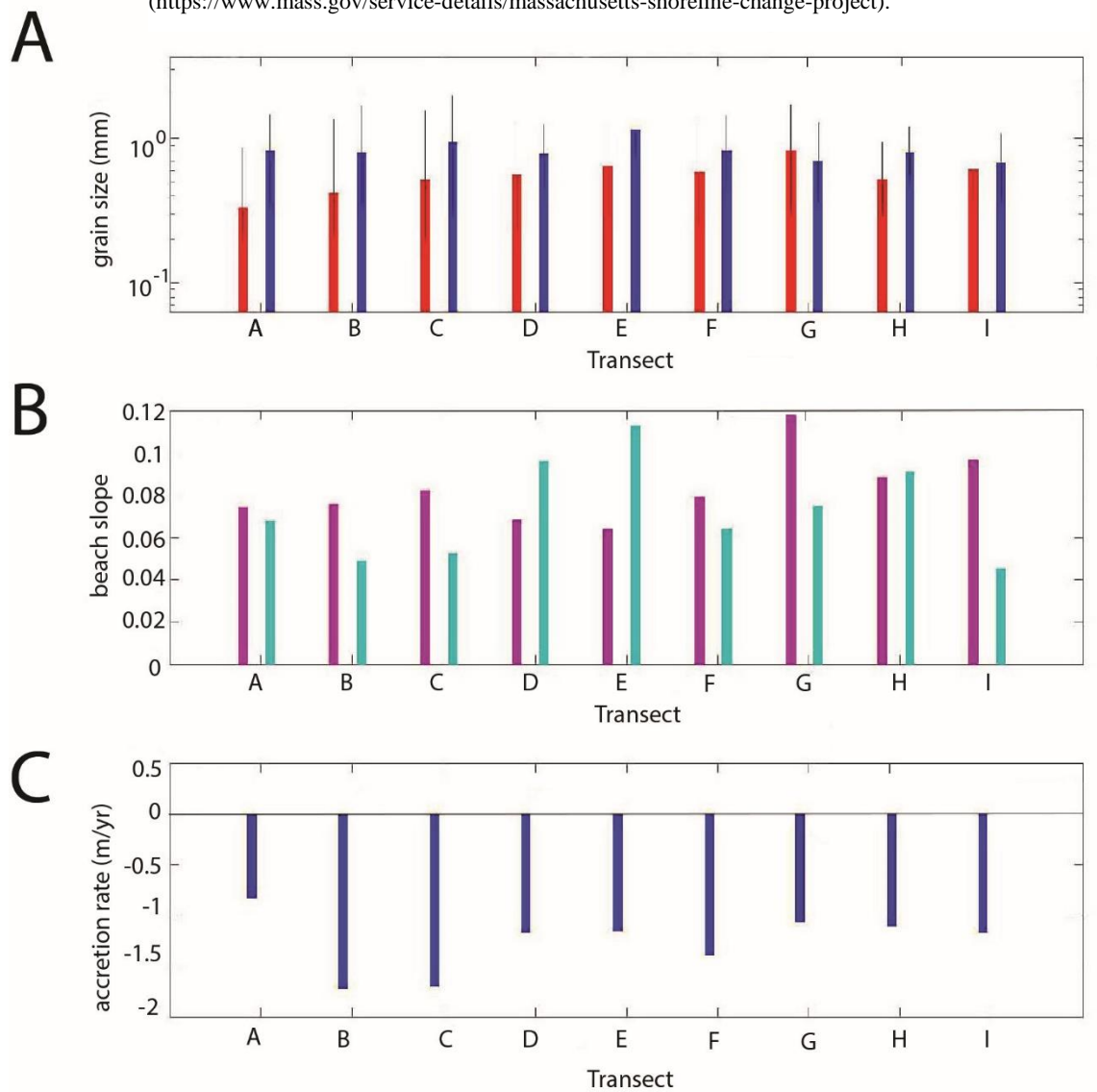


Figure 4: Mean off-shore Wave Height vs. Tidal Range: Mean off-shore wave height vs. tidal range at each study site. Figure adapted from Fitzgerald and Van Heteran (1999) and based on original classification scheme of Hayes (1979). Shapes represent geomorphology and colors represent sediment sources described shown later in Figures 10 and 11.

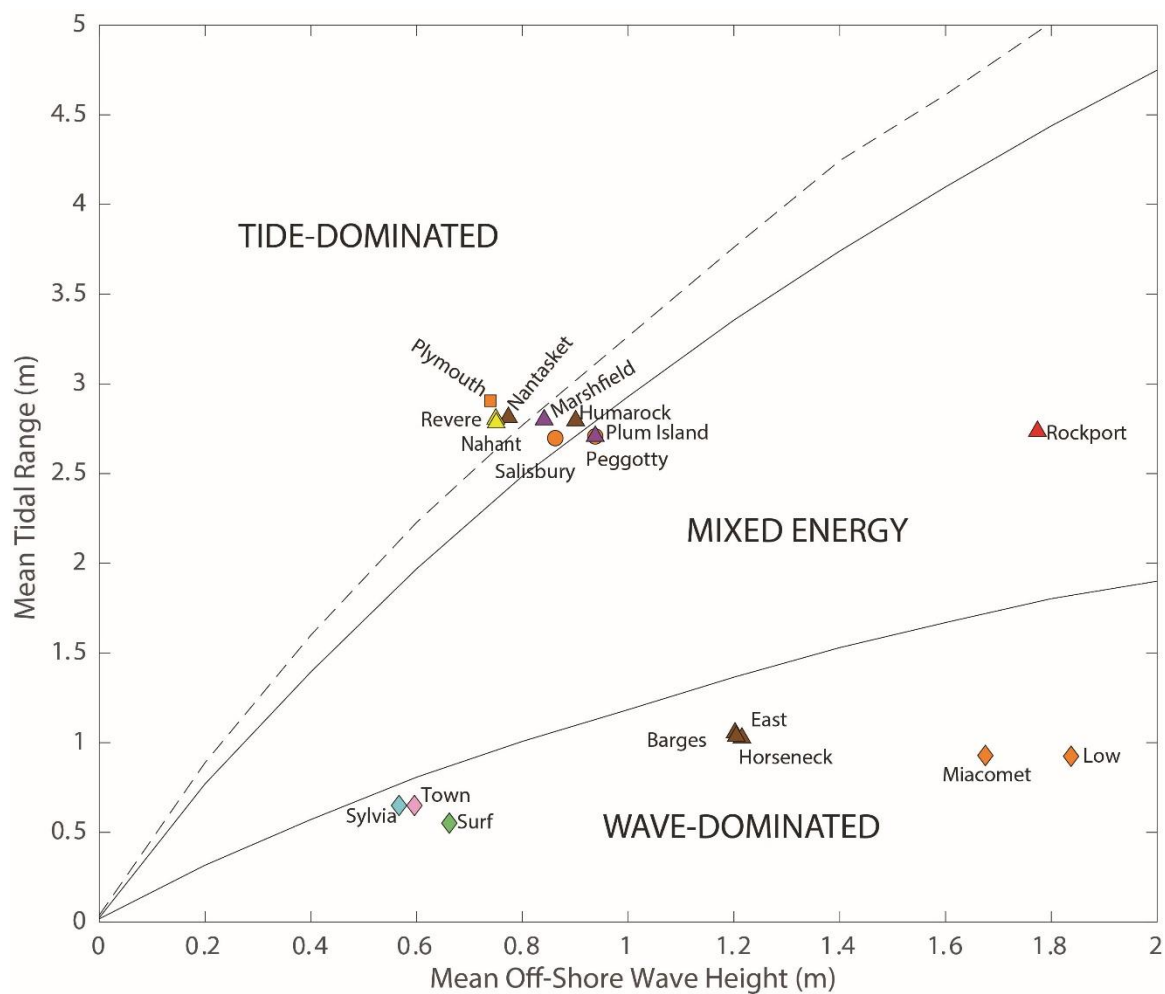


Figure 5: Geomorphic Classification of Massachusetts: General distribution of Fitzgerald and Van Heteran (1999) beach types in Massachusetts and example aerial images of each.

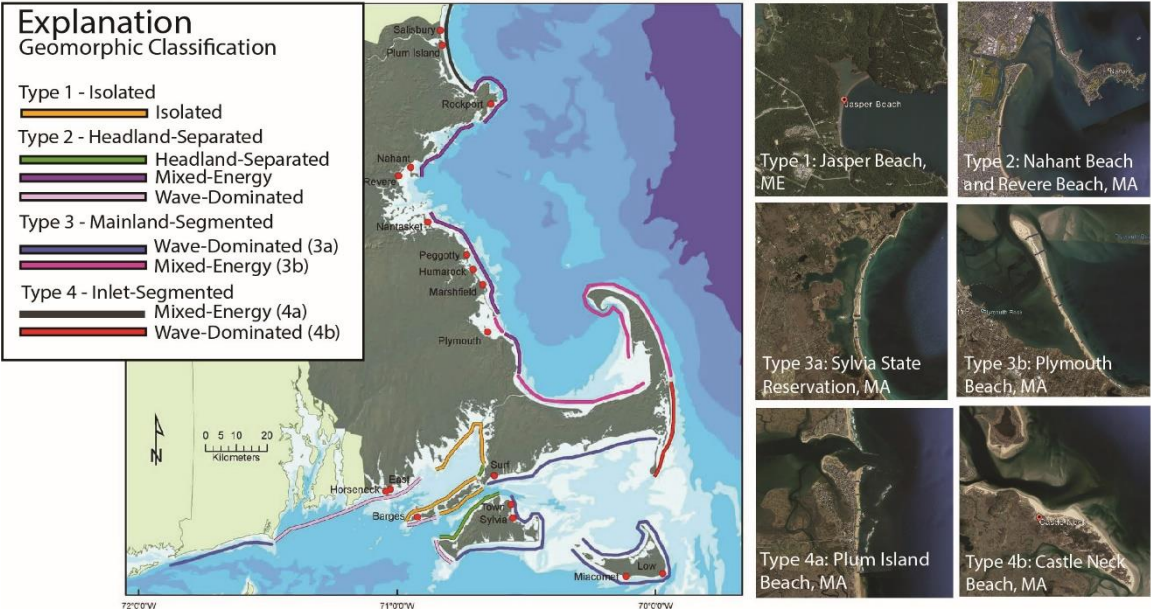


Figure 6: Surficial Geology of Massachusetts: Used to interpret surficial sediment source for each beach. Inset maps of six regions show arrows pointing to each of the study sites. Adapted from (Stone et al., 2006; Stone et al., 2011; Stone and DiGiacomo-Cohen, 2009; Stone and DiGiacomo-Cohen, 2015).

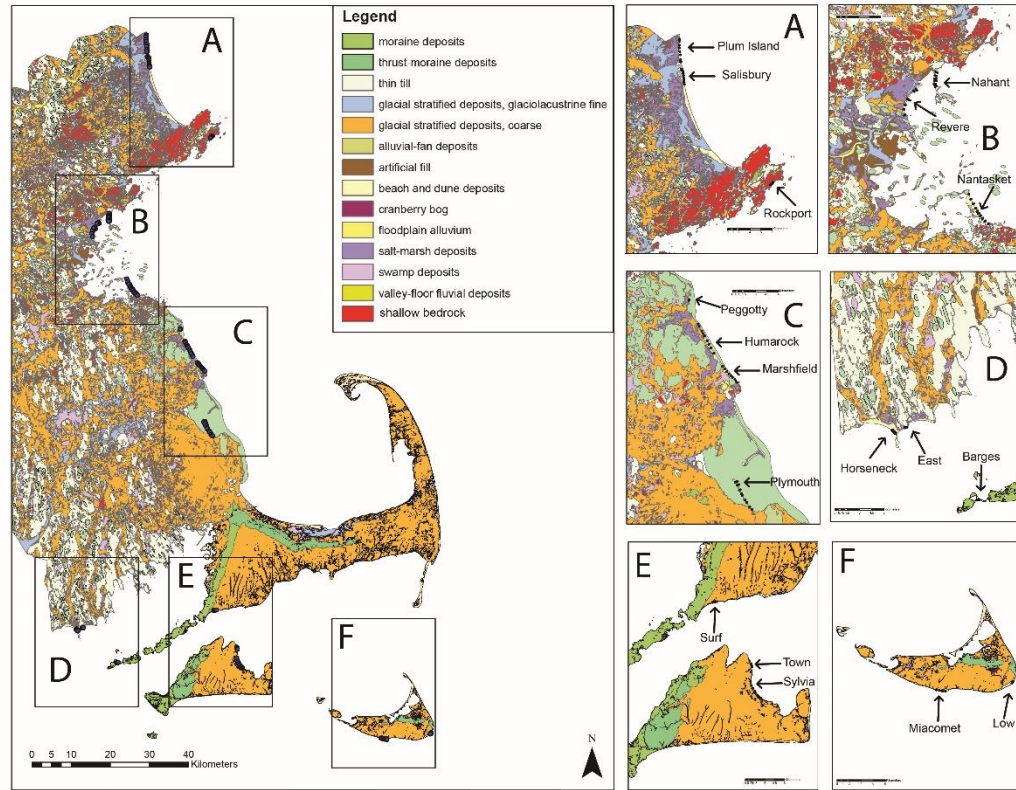


Figure 7: Beach Averaged Inter-tidal Beach Slope vs. Inter-tidal Median Grain Size: Beach averaged inter-tidal beach slope vs. inter-tidal median grain size for summer (solid symbols) and winter (plus signs). Shapes represent geomorphology and colors represent sediment source further described in Figure 10.

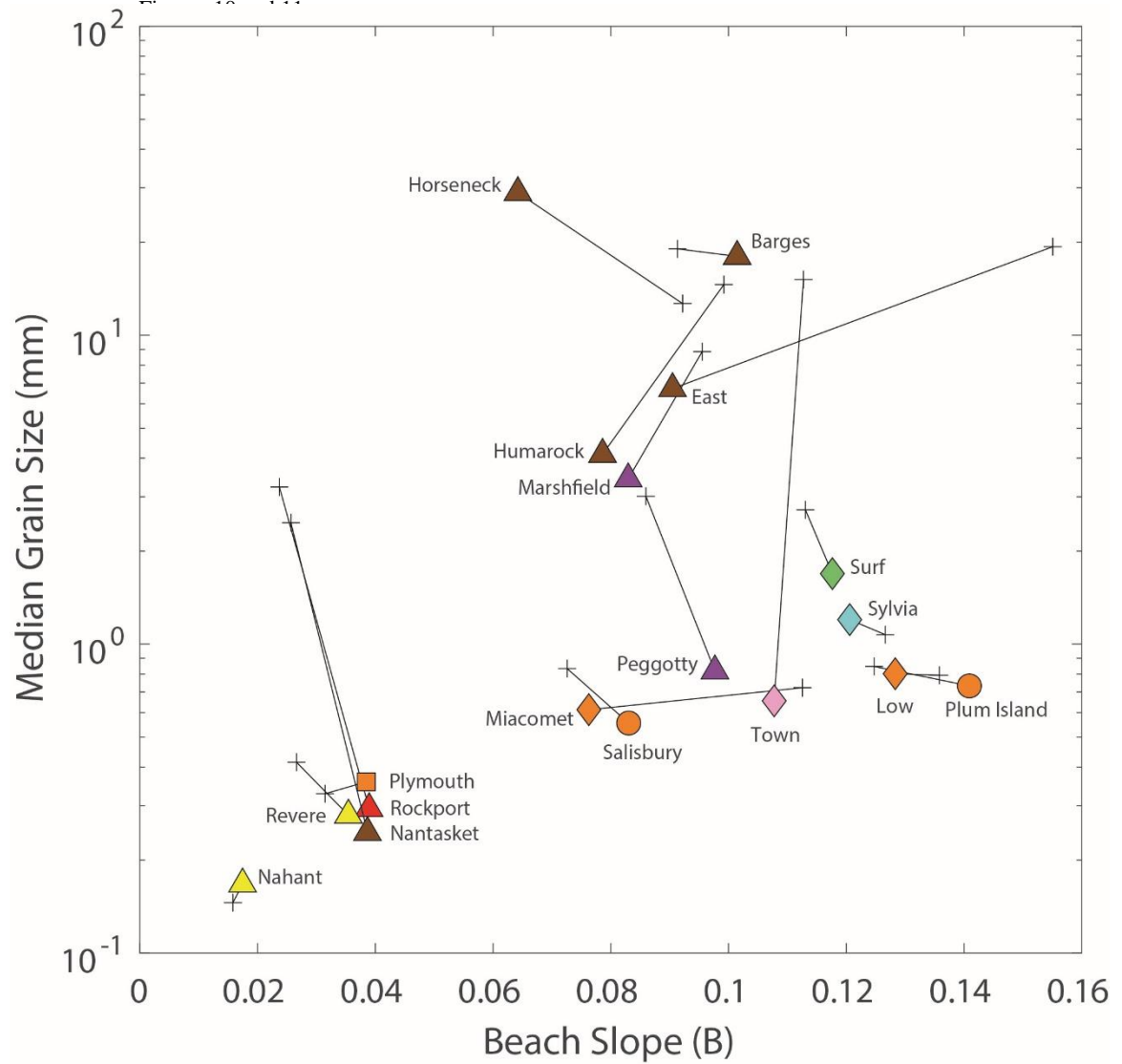


Figure 8: Beach Averaged Beach Slope vs. Median Grain Size for MA & U.S. Beaches: Average beach slope vs. median grain size for Massachusetts beaches (red), against measurements by Bascom (1951) for beaches on the West Coast (green) and East Coast from New Jersey to Florida (blue). Error bars for study data indicate range for winter and summer surveys. Dotted, solid and dashed lines represent average beach slope vs. median grain size relationship proposed by Weigel (1964) for protected, moderately protected and exposed protected beaches, respectively. Figure adapted from (Weigel, 1964).

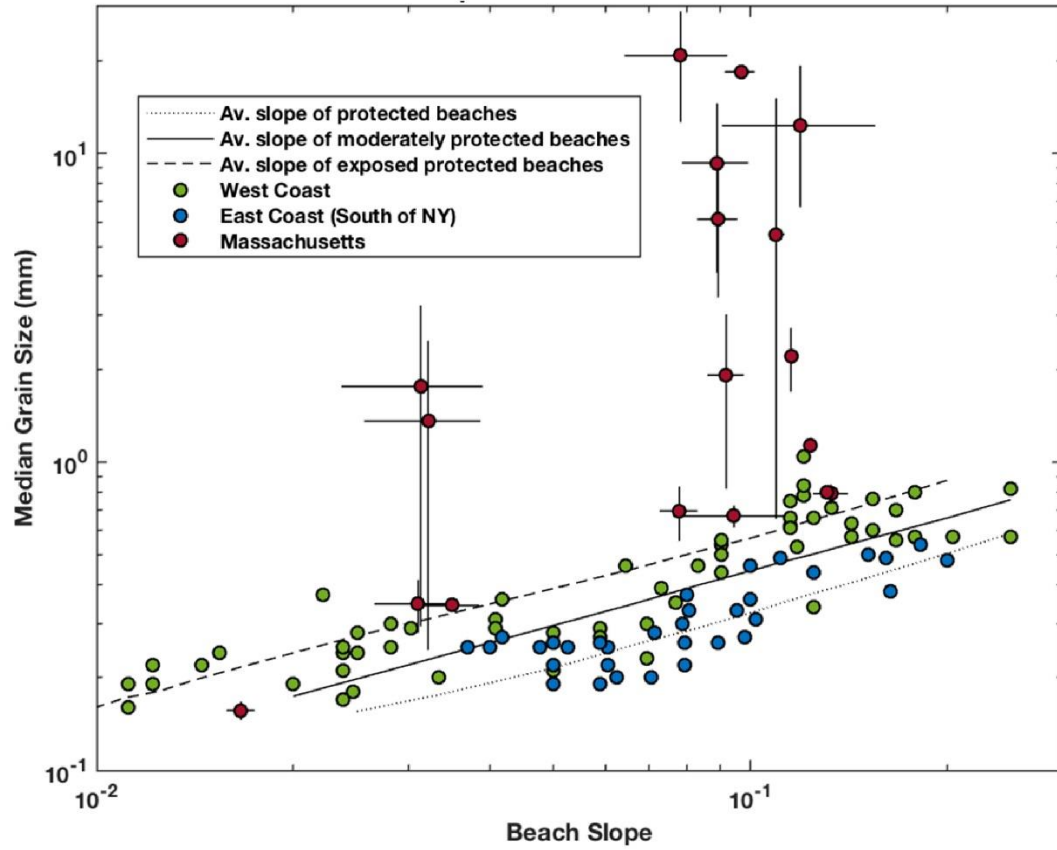


Figure 9: Iribaren Number (ξ) vs. Surf Scaling Parameter (Ω): Comparison of non-dimensional settling velocity surf parameters (Ω) vs. Iribarren Number (ξ). Values derived from beach averages of inter-tidal slope and D_{50} grain size, as well as local wave climatology obtained by COAWST simulations (Warner et al., 2010). Regions of dissipative, intermediate, and reflective wave breaking conditions are defined by Iribarren Number. Proposed regions for reflective and dissipative conditions using Ω are <1.5 and >5 respectively.

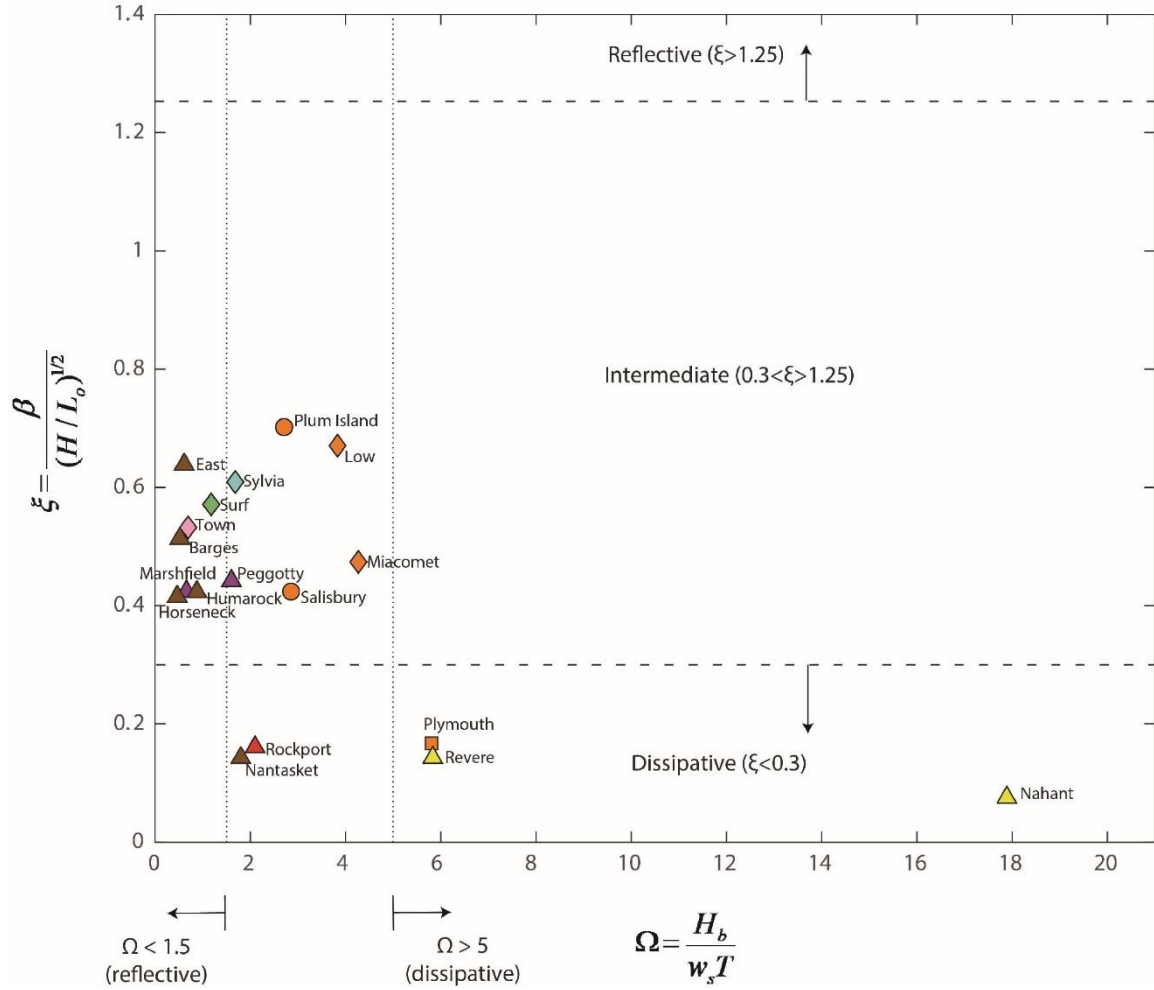


Figure 10: Beach Averaged Median Grain Size vs. Geomorphology: Beach averaged median grain size vs. barrier-coastline type as classified by Fitzgerald and Van Heteran (1999). Shapes represent their geomorphic setting (i.e. triangle is a 'Type 2' beach).

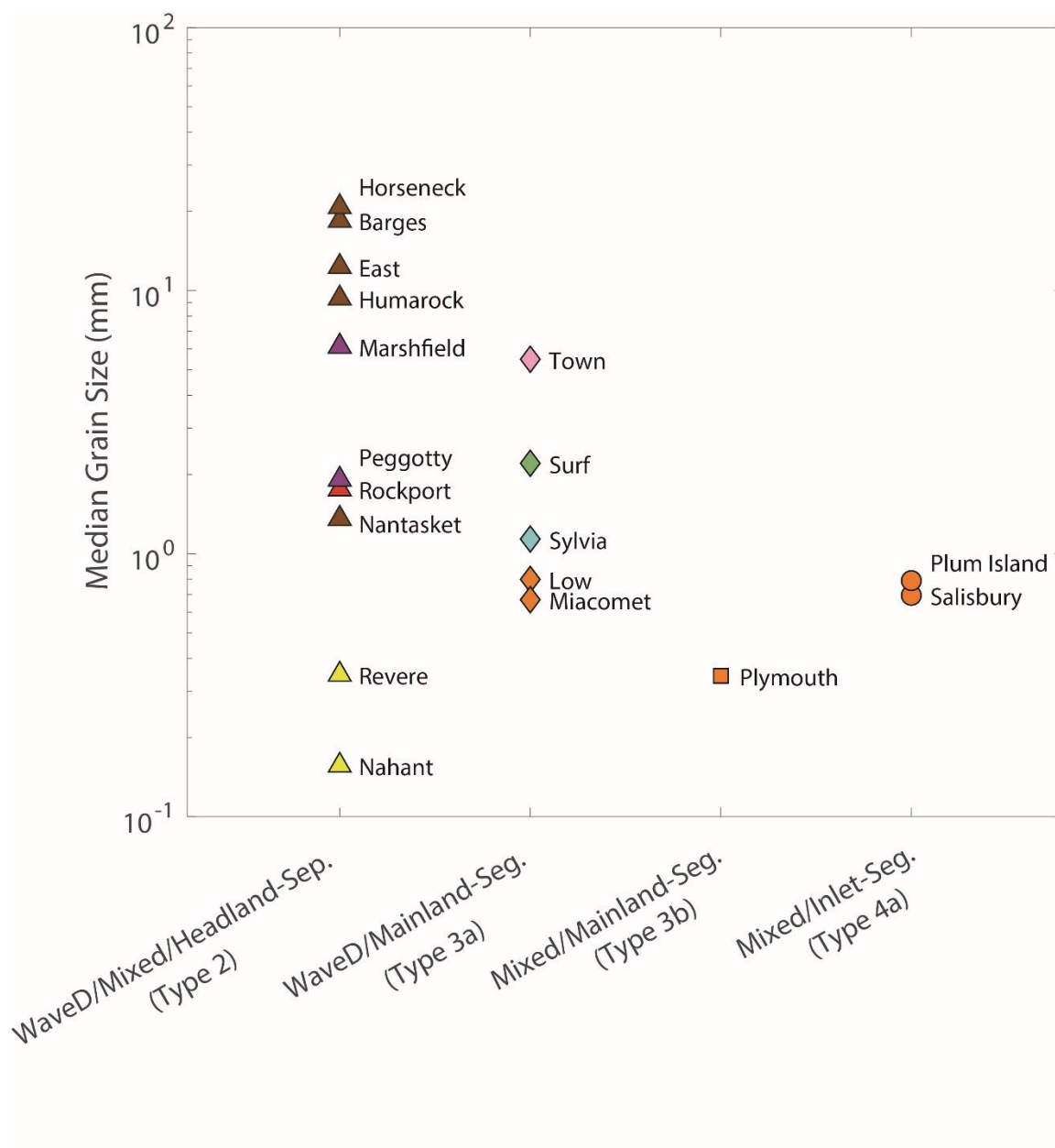


Figure 11: Beach Averaged Median Grain Size vs. Source Material: Neighboring surficial geology (i.e. source material) vs. beach average D_{50} grain size. 'CSD' are coarse stratified deposits. Site abbreviations include Plum Island (P.I), Salisbury (Sal.), Horseneck (Hors.) and Humarock (Hum.). Colors represent associated surficial geology (i.e. orange is CSD>90%).

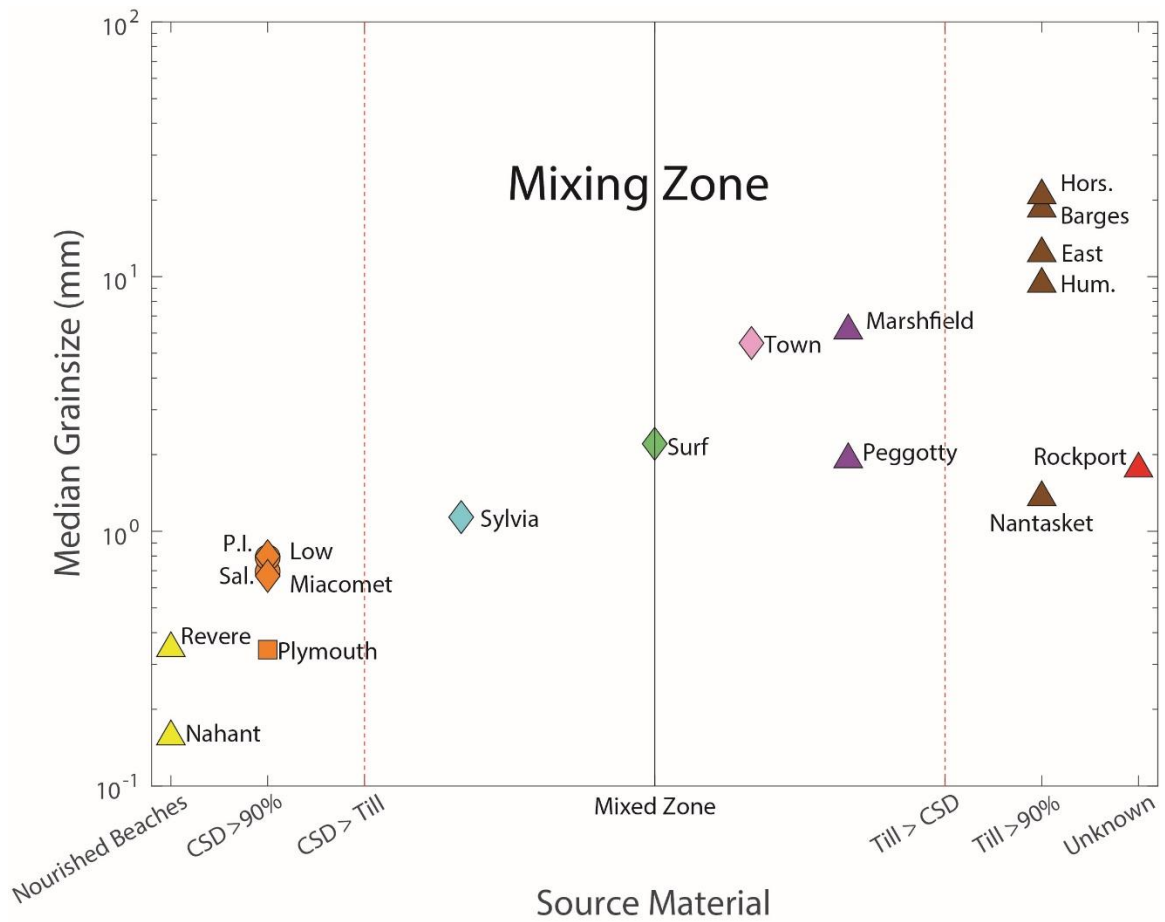
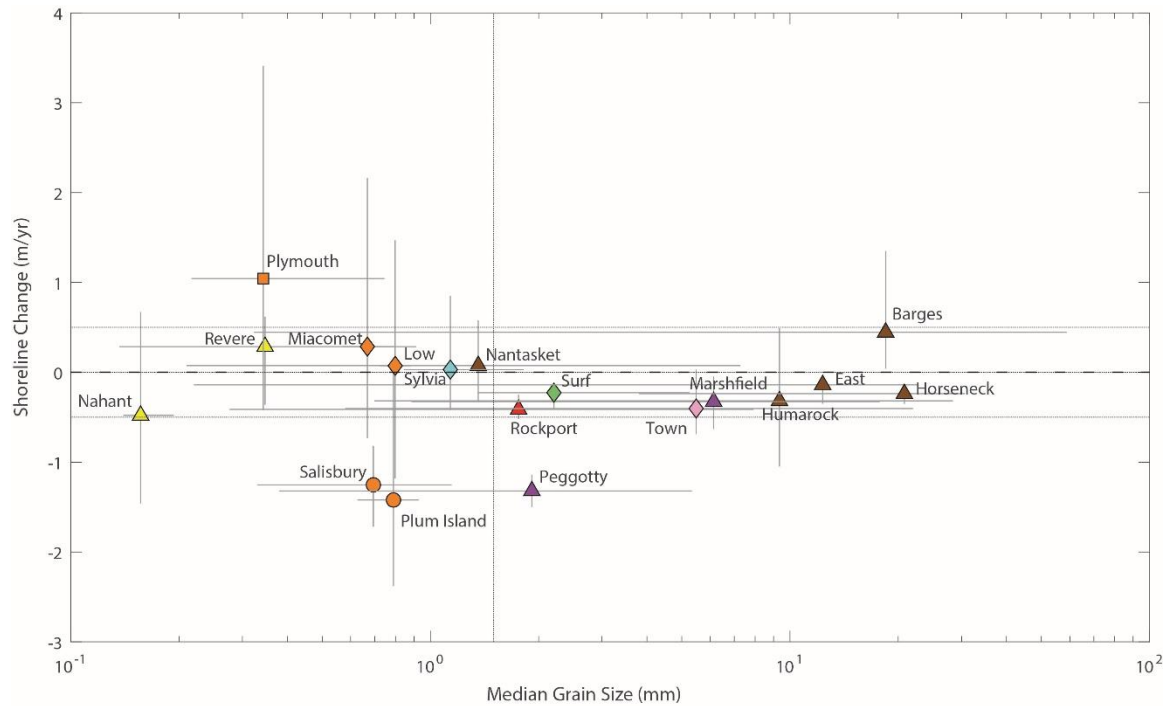


Figure 12: Shoreline Change vs. Beach Averaged Median Grain Size: Beach averaged values of D_{50} grain size and shoreline change. Shoreline change above and below zero indicates locations of accretion and erosion, respectively. Error bars represent maximum and minimum values for beach transects.



BIBLIOGRAPHY

Anthony, E.J., 1998, Sediment-Wave Parametric Characterization of Beaches. *Journal of Coastal Research*, Volume 14, no. 1., pp. 347–352. JSTOR, www.jstor.org/stable/4298783.

Barnhardt, Walter, A., Andrews, Brian, D., Ackerman, Seth, D., Baldwin, Wayne, E. and Hein, Christopher, J., 2009, High-Resolution Geologic Mapping of the Inner Continental Shelf: Cape Ann to Salisbury Beach, Massachusetts. U.S. Geological Survey. Open File Report.

Bascom, W.N., 1951, The Relationship between sand size and beach-face slope. *Transactions of the American Geophysical Union*, Volume, 32, no. 6, pp. 866-874.

Battjes, J.A., 1974, Surf Similarity. *Proceedings 14th International Conference on Coastal Engineering*. pp. 466-480.

--- , Beach Erosion Board, Interim report, 1933.

Belknap, D.F., Shipp, R.C., Kelley, J.T. and Schnitker, D., 1989, Depositional sequence modeling of the late Quaternary geologic history, west-central Maine coast. In: *Studies in Maine Geology 5: Quaternary Geology* (E. by R.D. tucker and R.G. Marvinney). Department of Conservation Maine Geological Survey, Augusta. pp. 29-46.

Bruun, Per, and F. Gerritsen., 1961, By-Passing of Sand by Natural Action at Coastal Inlets and Passes. *Transactions of the American Society of Civil Engineers* 126.4. pp. 823-850.

Buynevich I.V., FitzGerald D.M., 2001, Styles of coastal progradation revealed in subsurface records of paraglacial barriers: Duxbury, Massachusetts, USA. *Journal of Coastal Research*. pp. 194-208.

Buynevich I.V., FitzGerald D.M., 2002, Organic-rich facies in paraglacial barrier lithosomes of northern New England: preservation and paleoenvironmental significance. *Journal of Coastal Research*. Volume 36, no. 1., pp. 109-117.

Dean, R.G., and Dalrymple, D.A., 2001, *Coastal Processes with Engineering Applications*. Cambridge University Press.

Dougherty A.J., FitzGerald D.M., Buynevich I.V., 2004, Evidence for storm-dominated early progradation of Castle Neck barrier, Massachusetts, USA. *Marine Geology*. pp. 123-134.

FitzGerald D.M., Buynevich I.V., Rosen P.S., 2001, Geological evidence of former tidal inlets along a retrograding barrier: Duxbury Beach, Massachusetts, USA. *Journal of Coastal Research*. pp. 437-448.

Fitzgerald D.M., Van Heteran, S., 1999, Classification of paraglacial barrier systems: coastal New England, USA. *Sedimentology*. Volume 46, pp. 1083-1108.

FitzGerald, D.M., Van Heteren, S., Montello, T.M., 1994, Shoreline processes and damage resulting from the Halloween Eve storm of 1991 along the north and south shores of Massachusetts Bay, USA. *Journal of Coastal Research*. pp. 113-132.

Fitzgerald, M.D., 1993, Formation and Evolution of Multiple Tidal Inlets Coastal and Estuarine Studies, American Geophysical Union. Volume 44, pp. 1-61.

Forde T.C., Nedimović M.R., Gibling M.R., Forbes D.L., 2016, Coastal evolution over the past 3000 Years at Conrads Beach, Nova Scotia: the influence of local sediment supply on a Paraglacial Transgressive system. *Estuaries and coasts*. Volume 39, no. 2., pp. 363-84.

Gourlay, M.R., van der Meulen, T., 1968, Beach and Dune Erosion Tests. *Proc, 11th Int. Conf. on Coastal engineering*, London, 1968, Volume 1, pp. 701-707.

Gutierrez, B. T., Plant, N.G., and Thieler, E.R., 2011, A Bayesian network to predict coastal vulnerability to sea level rise, *J. Geophys. Res.*, pp. 116, F02009, doi: 10.1029/2010JF001891.

Guza, RT, & Inman D.L. 1975. Edge Waves and Beach Cusps. *Journal of Geophysical Research-Oceans and Atmospheres*.

Hayes, M.O., 1979, Barrier island morphology as a function of tidal and wave regime. In: *Barrier Islands from the Gulf of St. Lawrence to the Gulf of Mexico* (Ed. By S.P. Leatherman), pp. 1-27. Academic Press, New York.

Hein C.J., FitzGerald D.M., Buynevich I.V., Van Heteren S., Kelley J.T., 2014, Evolution of paraglacial coasts in response to changes in fluvial sediment supply. *Geological Society, London, Special Publications*. pp. 388-415.

Hill H.W., Kelley J.T., Belknap D.F., Dickson S.M., 2004, The effects of storms and storm-generated currents on sand beaches in Southern Maine, USA. *Marine Geology*. Volume 210, Issues 1-4, pp.149-68.

Inman, D.L., 1953 Areal and seasonal variations in beach and nearshore sediment at La Jolla, California, U.S. Army, Corps of Engineers, Beach Erosion Board, Tech. Memo. No. 39.

Inman, D. L. 1949. Sorting of sediments in the light of fluid mechanics. *J. sedim, Petrol.*, Volume 19, pp. 51–70.

Irish, J.D., Signell, R.P., 1992, Tides of Massachusetts and Cape Cod Bays. Woods Hole Oceanographic Institution.

Jackson, D.W.T., Cooper, J.A.G., and del Rio, L., 2005, Geological control of beach morphodynamic state. *Marine Geology*, Volume 216, pp. 297-314.

Kelley, J.T., Dickson, S.M., Belknap, D.F. and Stuckenrath, R. Jr., 1992, Sea level change and late Quaternary sediment accumulation on the southern Maine inner continental shelf. In: *Quaternary Coasts of the United States: Marine and Lacustrine Systems* (Ed. By C.H. Fletcher and J.F. Wehmiller), Spec. Pub. Soc. Econ. Paleont. Miner., Volume 48, pp. 23-34.

Kelley, J.T., Belknap, D.F. and Shipp, R.C., 1989, Sedimentary framework of the southern Maine inner continental shelf: influence of glaciation and sea level change. In: *Studies Related to Continental Margins* (Ed. By M.C. Hunt and S.V. Doenges), *Mar. Geol.*, Volume 90, pp. 139-147.

Kelley, J.T., Barber D.C., Belknap D.F., FitzGerald D.M., Van Heteren, S., Dickson S.M., 2005, Sand budgets at geological, historical and contemporary time scales for a developed beach system, Saco Bay, Maine, USA. *Marine Geology*. Volume 214., Issues 1-3, pp. 117-42.

Komar, P.D., 1976, *Beach processes and Sedimentation*, Prentice-Hall, New Jersey. pp. 429.

Leopold, L. B., 1970, An improved method for size distribution of stream bed gravel. *Water Resource. Res.*, Volume 6, no. 5., pp. 1357–1366.10.1029/WR006i005p01357

Masselink, G., Hughes, Michael, G., Knight, Jasper., 2011, *Introduction to coastal processes and geomorphology*. Second Edition. Hodder Education, an Hachette UK Company.

Masselink, G., and Short, A.D., 1993, The effect of tide range on beach morphodynamics and morphology: A conceptual beach model. *Journal of Coastal Research*, Volume 9, no. 3., pp. 785-800.

Martinez, M.L., et al., 2007, The coasts of our world: Ecological, economic and social importance, *Ecological Economics*, Volume 63, Issues 2-3, pp. 254-272. ISBN: 0921-8009.

McLean, R. F., Kirk R. M., 1969, Relationships between grain size, size-sorting, and foreshore slope on mixed sand - shingle beaches, *New Zealand Journal of Geology and Geophysics*, Volume 12, no. 1, pp. 138-155.

Oldale, Robert. N., 2001, Cape Cod, Martha's Vineyard, & Nantucket: The Geologic Story. On Cape Publications., ISBN: 0-9653283-5-X

Patrick., D.L., Patrick, 2014, Administration Celebrates the Completion and Dedication of the 'Philip. N. Carney Causeway' in Nahant. Commonwealth of Massachusetts: Executive Office of Energy and Environmental Affairs.

Revere Beach Partnership 501 (c)(3), 2003, <https://www.reverebeachpartnership.com>.

Revere Beach Shore and Bank Protection Project, 2015, US Army Corps of Engineers. <https://www.nae.usace.army.mil/Missions/Civil-Works/Shore-Bank-Protection/Massachusetts/Revere/>.

Short, A.D., 1996, The role of wave height, period, slope, tide range and embaymentisation in beach classifications: a review, *REV CHIL HN*, Volume 69, no. 4., pp. 589-604.

Short, A.D., and Wright, L.D., 1983, Physical Variability of Sandy Beaches. *Sandy Beaches as Ecosystems, Developments in Hydrobiology.*, Volume 19, pp. 133-144.

Short, A. D., 1979, Three Dimensional Beach-Stage Model. *The Journal of Geology*, vol. 87, no. 5, pp. 553-571. JSTOR, www.jstor.org/stable/30070742.

Stone, J.R., Stone, B.D., DiGiacomo-Cohen, M.L., Mabee, S.B., 2018, Surficial Materials of Massachusetts: A1:24,000-Scale Geologic Map Database, in press.

Stone, B.D., Stone, J.R., DiGiacomo-Cohen, M.L., and Kincare, K.A., comps., 2011, Surficial geologic map of the Norton-Manomet-Westport-Sconticut Neck 23-quadrangle area in southeast Massachusetts: U.S. Geological Survey Open-File Report 2006-1260-F, 21 sheets, scale 1:24,000, pp. 22. text.

Stone, B.D., and DiGiacomo-Cohen, M.L., compilers, 2009, Surficial geologic map of the Pocasset-Provincetown-Cuttyhunk-Nantucket 24-quadrangle area of Cape Cod and islands, southeast Massachusetts: U.S. Geological Survey Open-File Report 2006-1260-E.

Stone, B.D., Stone, J.R., and DiGiacomo-Cohen, M.L., 2006, Surficial Geologic Map of the Salem-Newburyport East-Wilmington-Rockport 16 Quadrangle Area in Northeast Massachusetts: U.S. Geological Survey Open-File Report 2006-1260-B.

Stauble, D.K., 2005, A review of the role of grain size in beach nourishment projects, U.S. Army Engineer Research and Development Center Coastal and Hydraulics Laboratory.

Thieler, E.R., Smith, T.L., Knisel, J.M., Sampson, D.W., 2013, Massachusetts Shoreline Change Mapping and Analysis Project, 2013 Update. Prepared in cooperation with the Massachusetts Office of Coastal Zone Management. USGS Open-File Report 2012-1189.

Thieler, E. R., and Hammar-Klose E.S., 1999, National assessment of coastal vulnerability to future sea-level rise: Preliminary results for U.S. Atlantic Coast, U.S. Geol. Surv. Open File Rep., pp. 99-593.

Udden, J. A. 1914, Mechanical composition of clastic sediments. Geological Society of America Bulletin, Volume 25, pp. 655-744. Bibcode:1914GSAB...25..655U. doi:10.1130/GSAB-25-655.

Warner, John, C., Armstrong, Brandy, He, Ruoying, and Zambon, Joseph, B., 2010, Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System. Ocean Modelling, Volume 35, pp. 230-244.

Wiegel, Robert L., 1964, Oceanographical Engineering. Dover Civil and Mechanical Engineering Publications. ISBN: 048616019X

Wright, L.D., Chappell, J., Thom, B.G., Bradshaw, M.P., Cowell, P., 1979, Morphodynamics of reflective and dissipative beach and inshore systems: Southeastern Australia. Marine Geology, Volume 32, Issues 1-2, pp. 105-140.

Wright, L.D., Short, A.D., 1984, Morphodynamic variability of surf zones and beaches: A synthesis. *Marine Geology*, Volume 56, Issues 1-4, pp. 93-118. ISSN:0025-3227

Wolman, M.G., 1954, A method of sampling coarse river-bed material. *Transactions of the American Geophysical Union*, Volume 35, no. 6, pp. 951-956.

Wohl, E. E., Anthony, D. J., Madsen, S. W., and Thompson, D. M., 1996, A comparison of surface sampling methods for coarse fluvial sediments. *Water Resource. Res.*, Volume 32, no. 10, pp. 3219–3226.

Wentworth, Chester K., 1922, A Scale of Grade and Class Terms for Clastic Sediments. *The Journal of Geology*, Volume 30, no. 5, pp. 377–392. JSTOR, www.jstor.org/stable/30063207.

Zhang, Keqi., et al., 2001, Beach Erosion Potential for Severe Nor'easters. *Journal of Coastal Research*, Volume 17, no. 2, pp. 309–321. JSTOR, www.jstor.org/stable/4300181.